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14. ABSTRACT

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Establishment of a Hall Thruster Cluster

Prepared by

Professor Alec D. Gallimore

Department of Aerospace Engineering

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Abstract

Closed-Drift Hall thrusters (CDTs) can satisfy many of the spacecraft propulsion needs of the United States Air Force (USAF) for the next several decades. The combination of high specific impulse, high thrust efficiency, and high thrust density makes the CDT very attractive for a number of earth-orbit space missions. The USAF has recently identified the high-power (*e.g.,* 50-150 kW) CDT propulsion system as the baseline approach for a variety of missions including LEO-to-GEO orbital transfer vehicles (OTVs), space tugs, and servicing/re-supply vehicles for large orbital assets; *e.g.,* Space Based Laser. While the evolutionary path for scaling current 5-kW-class CDTs to 50 kW is uncertain because of a variety of issues, it is clear that testing 50-kW-class CDTs in current or near-term test facilities is of concern given the fact that an order-of-magnitude increase in pumping speed would be necessary to satisfy pressure requirements. In response to this issue, the USAF has embarked on the concept of clustering; *i.e.,* the use of smaller Hall thrusters in a propulsion array. This would allow a single, smaller CDT that is amenable to ground-based testing to be used in an array consisting of up to 16 thrusters. However, there is no fundamental understanding of how clustered thrusters operate or how one can use single-engine ground-based data to predict the performance, cross talk (among the engines), lifetime, and spacecraft integration issues for the cluster. To this end, DURIP funds were used to develop a Hall thruster cluster test facility centered around the University of Michigan Large Vacuum Test Facility and a 2x2 cluster of BUSEK 600 W BHT-600 Hall thrusters. This capability will facilitate our three-year program to address the issue of high-power CDT operation and to provide insight on how chamber effects influence CDT engine/cluster characteristics.

Background Information

Propulsion systems having high exhaust velocities (Ve>10 km/s) are desirable for a variety of space missions. In order for a propulsive system not to require an inordinate amount of propellant, its exhaust velocity should be of the same order as or greater than the characteristic velocity increment (Delta-V) required for a given space mission. Studies have shown that for orbit transfer missions of interest by NASA and the DoD, a characteristic velocity increment of over six kilometers per second may be necessary[1]. Furthermore, experience gleaned from operation *Desert Storm* shows the need for military space assets to be rapidly repositioned without excessive use of onboard propellant; *i.e.*, the need for high specific impulse propulsion systems of moderate thrust.

Cryogenically-fueled chemical rockets, which rely on the intrinsic energy available from the chemical reactions of their constituent propellants, are inherently limited to exhaust velocities below 5 km/s.[2] Chemical rockets, which use space storable propellants such as hydrazine are limited to exhaust velocities of about 3 km/s[2]. Thus, propulsion systems that produce exhaust velocities considerably higher than those obtained with chemical systems would greatly enhance a variety of orbital space missions.

Ideally, an engine which would be used as the primary source of propulsion for satellite station-keeping and orbit repositioning in modern spacecraft should produce an exhaust velocity between 10 and 25 km/s.[3] To achieve this performance, a propulsion system must accelerate its propellant gas without relying on energy addition through chemical reactions. One approach is the application of electrical energy to propellant in the form of electrical heating and/or electric and magnetic body forces. This type of propulsion system is commonly known as electric propulsion (EP).

EP can be categorized into three groups:[4] i) *Electrothermal Propulsion Systems* in which a gas is electrically heated, either with resistive elements or through the use of an electric arc, and is subsequently expanded through a supersonic nozzle to produce thrust; ii) *Electromagnetic Propulsion Systems* which use electromagnetic body forces to accelerate a highly-ionized plasma; and iii) *Electrostatic Propulsion Systems* which use electric fields to accelerate ions.

In addition to possessing suitable exhaust velocity, an EP system must also be able to convert onboard spacecraft power into directed kinetic power of the exhaust stream efficiently (*i.e.*, possess high thrust efficiency) and must generate suitable thrust to ensure reasonably short deployment times.

Electrothermal systems have limited utility for this role because of performance constraints placed on them by excessive frozen flow and electrode losses.[5,6,7] The specific impulse and thrust efficiency of arcjets operating on standard space-storable propellants (*e.g.*, hydrazine) is limited to less than 650 seconds and 41%, respectively. Recent Air Force arcjet tests have demonstrated specific impulses of over 800 seconds on ammonia. Steady-state electromagnetic systems have demonstrated high thrust efficiencies only at power levels that far exceed those generated onboard current or anticipated spacecraft.[8,9] Gridded electrostatic engines (*e.g.*, ion thrusters), which can achieve large exhaust velocities (Ve>50 km/s) at high thrust efficiencies (>70%), have traditionally demonstrated efficient performance at exhaust velocities above 30 km/s;[4,10,11] beyond the desired range for orbit transfer missions.[3] The high specific impulse of the ion thruster means that for a given spacecraft power level, it will generate less thrust than a lower Isp counterpart, resulting in larger trip times and a demand for longer thruster life. Furthermore, ion thrusters pay a penalty for its high power processing specific mass due to its large operating voltages (*e.g.*, 1100 V) and are limited in thrust density by space-charge effects, making ion thrusters considerably bulkier than other EP systems.[4]

Therefore, the ideal propulsion system for orbit transfer missions and for satellite station-keeping is a compact engine of high thruster density that efficiently accelerates propellant (*e.g.*, through electrostatic means) to modest exhaust velocities while requiring discharge voltages of less than 1000 V. As is shown below, the Hall thruster is a device that fulfills these requirements.

The Hall Thruster

The Hall thruster is an electrostatic engine that was developed in the 1960s to alleviate the thrust density limitation of ion thrusters that results from space-charge effects within the acceleration volume. Hall thrusters were also attractive from the standpoint that since grids are not required to accelerate ions, they do not suffer from the large grid erosion rates of ion thrusters. Interest in the Hall thruster waned in the early 1970's, however, because of budgetary cuts and because American researchers were never able to demonstrate that these engines could operate at thrust efficiencies near those achieved with ion thrusters.[12,13,14] As such, Hall thruster research essentially disappeared in the U.S. between 1972 and 1985. From 1985 to 1990, Ford Aerospace (now Space Systems/Loral), in conjunction with the NASA Lewis Research Center (now the John Glenn Research Center at Lewis Field [GRC]), funded a small research effort to determine if Hall thrusters could be used for North-South station-keeping (NSSK).[15,16] This program proved to be unsuccessful and was abandoned.

Throughout this period, however, Hall thruster research flourished in the Soviet Union, ironically partly because Soviet engineers were never able to develop adequate grids for ion thrusters. Hall thrusters were first tested in space in 1971 with immediate success.[16,17] Since then, over one hundred Hall thrusters have been used on Soviet and Russian spacecraft, mostly as plasma contactors and for East-West station-keeping. However, in 1994 the first satellite to use Hall thrusters for North-South Stationkeeping (NSSK) was launched by Russia. Because of this and numerous experiments which show that Russian Hall thrusters are capable of generating specific impulses of 1500-2200 seconds at thrust efficiencies of 50% or more,[18] there has been a great deal of interest in using these engines on American spacecraft for NSSK and for orbit repositioning. For example, the Ballistic Missile Defense Organization (BMDO) in conjunction with NASA GRC and the Naval Research Laboratory (NRL) developed a flight experiment that used a Russian Hall thruster on a U.S. experimental satellite.[19] Space Systems/Loral (SSL) has announced that its next generation of communication satellites will use Hall thrusters for NSSK, perhaps as early as next year. Clearly this device, with performance far superior to that of arcjets, and which is better-suited for Earth orbit missions than gridded ion thrusters,[1] currently the most advanced propulsion system used on American spacecraft, would not only serve as an excellent thruster for orbit station-keeping and repositioning roles, but potentially could be scaled in power to propel orbit transfer vehicles and future planetary probes. Thus, GRC has recently issued two contracts for the development of two-stage Hall thrusters with performance equivalent to that of the NSTAR ion thruster flown on NASA's 1998 Deep Space 1 mission.

The Closed-Drift Hall Thruster

There are two types of Hall thrusters that have been studied at great lengths; the end-Hall thruster and the closed-drift thruster (CDT). Both engines, in principle, are capable of producing specific impulses in excess of 1500 seconds with xenon at a thrust efficiency of 50% or greater. However, it is the CDT, which has been developed and used in the former Soviet Union over the past forty years, that is of the most interest to the Western space technology community.

The CDT is a coaxial device in which a magnetic field that is produced by an electromagnet is channeled between an inner ferromagnetic core (pole piece) and outer ferromagnetic ring (Fig. 1). This configuration results in an essentially radial magnetic field with a peak strength of a few hundred gauss. This field strength is such that only the electrons are magnetized. In addition, an axial electric field is provided by applying a voltage between the anode and the downstream cathode. As the electrons stream upstream from the cathode to the anode, the **ExB** action on the electrons cause them to drift in the azimuthal direction, forming a Hall current. Through collisions, these electrons ionize propellant molecules that are injected through the anode and which are subsequently accelerated by the axial electric field. The mixture of electrons and ions in the acceleration zone means that the plasma is electrically neutral, and as such, is not space-charge limited in ion current (thrust) density. Since the magnetic field suppresses the axial mobility of the electrons while exerting essentially no effect on ion dynamics, the plasma can support an axial electric field with a potential difference close to the applied voltage between the electrodes. Thus, the bulk of the ions are accelerated to kinetic energies to within 85% of the applied discharge voltage.[12] This combination of processes accounts for the CDT's high thrust efficiency.

Russian CDTs come in two variants; the stationary plasma thruster (SPT) (also known as the magnet layer thruster) and the anode layer thruster (TAL). The main difference between these two devices is that the SPT uses a dielectric coating that usually contains boron nitride to electrically insulate its acceleration channel while the TAL uses channels made out metal. Performance characteristics of both engines are virtually identical. Although they vary in size and input power, CDTs that are currently being considered for NSSK typically operate at discharge voltages of 300 to 350 V, and thruster currents between 4.5 and 10 A, with xenon mass flow rates of 5 to 10 mg/s. As the discussion below will show, the power level (and therefore the current and mass flow rates) that will be needed in the near future will be considerably higher.

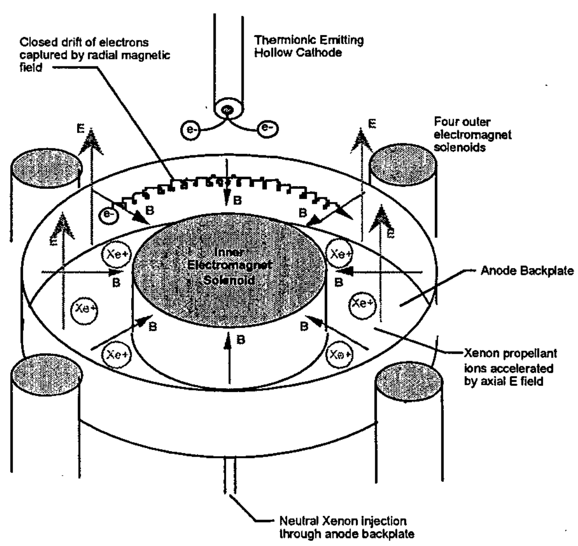

Figure 1: Schematical diagram of a closed-drift Hall thruster.

Motivation

Communication satellites are becoming both larger and more powerful. This fact is acknowledged throughout the EP community. Boeing Satellite Systems' recent development of the HS-702 satellite with up to 15 kW of solar array power and SS/L's announcement of the 2020 spacecraft with more than 20-25 kW of solar array power by 2003 suggests that EP systems will have to double or triple in power from the current 3-5 kW systems within the next decade to satisfy commercial spacecraft needs. This means that vacuum systems will have to be modified to handle the added propellant flow rates demanded by these higher-power thrusters. The Air Force Research Laboratory (AFRL), GRC, and laboratories in Europe have recently upgraded their pumping systems in anticipation of higher-powered thrusters. As will be discussed in the next section, while NASA and the USAF both require high-power Hall thruster systems for future missions, these agencies are taking somewhat different paths in achieving this goal.

The NASA Approach to High-Power Electric Propulsion: The Monolithic Hall Thruster

NASA has embarked on a program to develop high-power EP systems for a variety of missions including a piloted expedition to Mars within the next two decades. The baseline piloted mission to Mars uses a Solar Electric Propulsion (SEP) stage to raise a chemically-powered Mars Transfer (MT) stage to a highly elliptical orbit around the Earth. Once the MT stage is in the proper orbit, the crew uses a small, chemically-propelled vehicle to rendezvous with it. Once the crew is in place and the MT stage has been certified, it separates from the SEP stage and ignites its engines for the trip to Mars.

This scenario reduces both trip time (for the crew) and initial spacecraft mass by utilizing a high-performance SEP stage for much of the Delta-V. Moreover, since the SEP stage operates in proximity to the Earth, nuclear power is not needed for this mission. However, the key to developing the SEP stage is the utilization of powerful engines that posses high exhaust velocity, high thrust efficiency, and a wide range of exhaust velocities. To this end, NASA has initiated a program to design a 50-kW-class CDT—called the NASA "457"— by the end of this year and to test this engine next year. While NASA's eventual goal in terms of power for the 'monolithic' thruster that would be used to propel the Mars SEP stage has yet to be identified, given the fact that the propulsion system for this stage must process hundreds of kilowatts to several megawatts of power, clustering (*i.e.*, the use of multiple engines at once) will most-likely be necessary regardless.

The USAF Approach to High-Power Electric Propulsion: Clustering

The USAF anticipates the need for CDT propulsion systems capable of processing more than 100 kW of power for a variety of Air Force Space Command (AFSPC) vehicles in the not-too-distant future. These include orbital transfer vehicles (OTVs), space tugs (*e.g.*, for high-power space-based radar systems), and re-supply vessels; *e.g.*, for high-power space-based lasers. The multi-million dollar IHPRPT award given in recent years by the USAF to an industrial team comprised of SS/L, Atlantic Research Corporation, and the Russian design bureau FAKEL for the development of the 5-kW-class SPT-140 CDT attests to the importance of this technology to the defense community. More recently, the USAF awarded BUSEK with a contract to develop the 8-10 kW BHT-HD-8000 CDT, a 'next generation' CDT in terms of power. While the evolutionary path for scaling current 5-kW-class CDTs and next generation 10-kW-class CDTs to 100-plus kW devices is uncertain because of a variety of issues, it is clear that testing 100-plus-kW-class CDTs in current or expected test facilities poses a significant challenge.

The reason for this is that as thruster power is increased, its internal discharge chamber pressure tends to decrease to maintain efficient operation. However, thruster mass flow rate, and hence facility background pressure, increase proportionately with power for fixed thruster voltage (exhaust velocity). So as the power of the CDT increases, its internal pressure decreases and yet the background chamber pressure increases. This poses an issue not only for measuring high-power CDT performance and plume/contamination characteristics, but also for assessing engine life.

Since vacuum facilities capable of testing 100-plus-kW CDTs are unlikely to be available by the time these engine are needed (if at all in the foreseeable future), the USAF has decided to reach its high power goal through the use of clustering. Figure 2 shows the two approaches taken by the USAF and NASA to reach 100-plus-kW CDT propulsion; clustered and monolithic.

The idea behind the clustering approach is to use 'next generation' CDTs (8-10 kW thrusters) in a 4x4 array to achieve a total propulsion system power of 128-160 kW, system effective exhaust velocity of approximately 20 km/s, and a total engine thrust between 8 and 10 N. An engine such as the USAF-sponsored BUSEK BHT-HD-8000 would serve as an element of the thruster array. The challenge, therefore, is to ensure that a single element (thruster) can be adequately testing with existing facilities, and that a methodology is developed to predict cluster operating characteristics (*e.g.,* performance, life, spacecraft interaction) on the basis of experiments conducted with a single engine. Even a single next generation CDT will tax all but the very best test facilities in the nation. Moreover, even if NASA succeeds in developing 50 or 100 kW CDTs (the limit of NASA's test capability), it will still need to cluster these engines to achieve the thrust level needed for future missions.

Thus, modular, high-power CDT propulsion systems will undoubtedly be required both for USAF and NASA missions in the future. As such, our research will focus in ensuring that adequate methodologies are in place to properly test a single element of the cluster at chamber pressures that are perhaps greater than ideal, and that information gleaned from such tests can be applied to predict cluster characteristics.

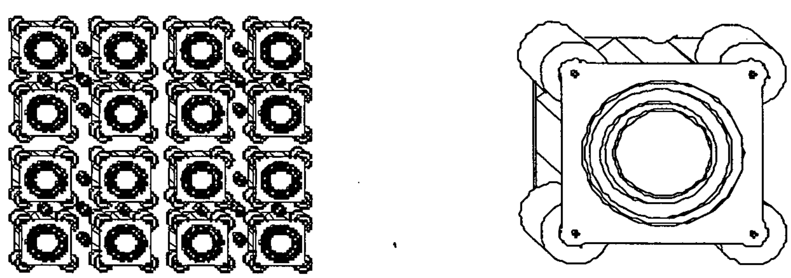

Figure 2: Two approaches to high-power Hall thruster propulsion (128 kW); 4x4 cluster of 8 kW CDTs (USAF), monolithic thruster (NASA).

Motivation for DURIP Request

One of the key factors that must be considered in any facility effects study involving thrusters of various power levels is CDT scaling. While several researchers in Russia and the U.S. have developed CDT scaling laws[12,1720,21] there is no universal agreement among them. However, these models all tend to reflect the following design trends, assuming that the CDT is geometrically scaled in size such that a characteristic length, L (usually considered the width between the inner and outer discharge chamber walls), exists and the voltage (*i.e.,* specific impulse) is fixed;

$$B \sim 1/L \quad (1)$$
$$P \sim 1/L \quad (2)$$
$$J \sim L \quad (3)$$

where B is the magnetic field strength, P is the discharge chamber pressure, and J is the discharge current. Thus, according to these scaling factors, a high-power CDT: (1) Must be physically larger since J and hence power (for fixed discharge voltage) scales with L; (2) Must operate at a lower chamber pressure to ensure that adequate ionization is maintained throughout the discharge chamber; and (3) Requires a smaller magnetic field to provide adequate electron confinement. The inverse relation between B and L can also be derived by considering the magnetic integral, (integral of Bdx where x is the axial coordinate) a quantity that has been shown to be a good similarity parameter for CDTs.* The power level at which these scaling laws, particularly Equation (1), breaks down is a subject of ongoing research. However, it appears that CDTs with input power levels in excess of 20 kW still adhere to these laws.

Figure 3 shows a plot of thruster power as a function of thruster size (discharge chamber outer diameter) derived from the referenced scaling laws. Also shown in the figure are CDTs developed by the Fakel design bureau in Russia (SPT series of thrusters) and the successful P5 laboratory-model CDT developed at the University of Michigan and AFRL. The figure shows that there is excellent agreement between the model and engines developed up to the 25 kW power level. Extrapolated engine sizes for 25-50 kW are shown as well. We note that the discharge chamber diameter does not increase linearly with power as the scaling laws above would suggest because the scaling length is usually chosen as the channel width and not the discharge chamber diameter.

The same scaling model used to generate Figure 3 was used to estimate the pressure within the discharge chamber of a CDT (Figure 4). While medium-power (1-5 kW) CDTs are predicted to have pressures of about 5×10^{-4} Torr—which is consistent with measurements[22] and modeling[23]—a 50 kW CDT will have chamber pressures a factor of five lower; *i.e.*, approaching 1×10^{-4} Torr. Thus, the internal pressure of 50 kW CDTs will approach the background pressure that many of today's test facilities can maintain with 5 kW thrusters. It may be argued that for a given CDT system power level that a modular system will be less sensitive to background pressure since the discharge chamber pressure of each engine will be larger than the discharge chamber of a monolithic thruster with the same power. The importance of minimizing facility effects by maintaining a low background pressure and large internal chamber volume will be reviewed in the next subsection.

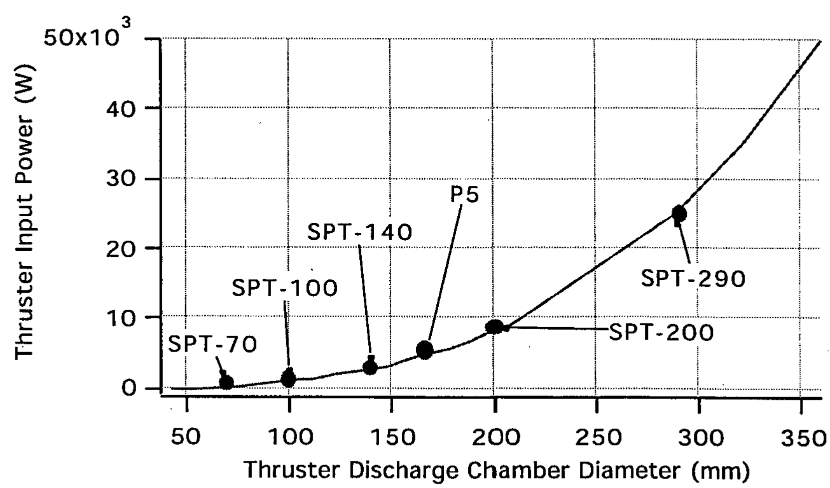

Figure 3: Thruster power vs. discharge chamber diameter.

* Use of this quantity as a scaling parameter also comes from assuming that Bohm cross-field electron diffusion processes are at play in CDTs, something which has been shown to be true by experiments[13]

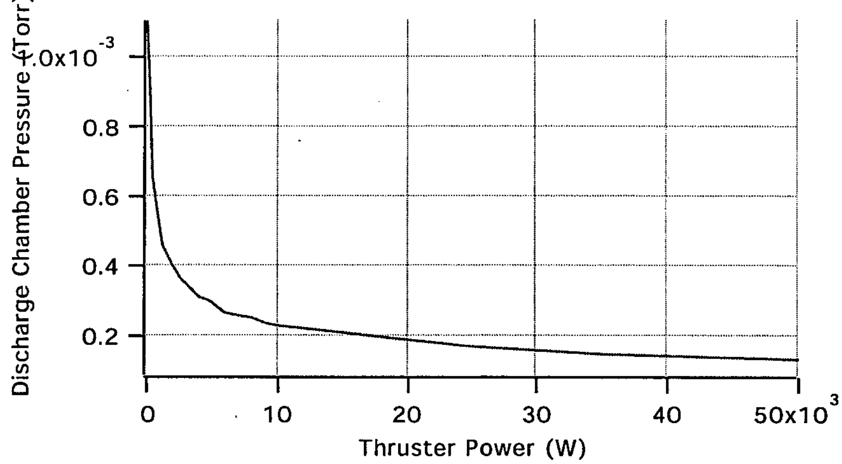

Figure 4: Discharge chamber pressure vs. thruster power

Influence of Facility Effects on Thruster Testing

Although CDTs have performance characteristics that make them attractive for Earth-orbiting missions, the complex nature of their operation is a source of concern from a spacecraft integration point-of-view. For example, CDTs that use dielectric channel coatings suffer from excessive insulator erosion. Much of this erosion is due to sputtering from energetic ions near the exit of the discharge chamber. TALs, on the other hand, which erode metal from its channel walls, may pose an even more serious threat to spacecraft health. Such erosion poses a potential hazard to spacecraft operation since ablated material could coat vital spacecraft surfaces like solar arrays and optics.

Since a non-negligible fraction of the exhausted particles travel at angles in excess of 45° from the thruster axis, plume divergence not only detracts from engine performance, but also results in damage to the spacecraft due to sputtering.[24] This issue will be even more pronounced when the engines are arranged in a cluster since the plume of one engine will interact with the plume of another. The erosion/deposition characteristics in the plume of CDTs are quite complex. Experiments have shown that in the central region (45°) of the plume, the energetic ions tend to remove deposited materials from structures in such a way that the net erosion rate overwhelms the surface deposition rate of thruster effluent material.[25] At higher angles with respect to the thruster axis of symmetry, however, the opposite is true: That is, the plume tends to remove material from objects placed near its axis of symmetry, and deposits matter on objects at higher angles.[26] The exact location where this transition occurs (and what parameters it may depend on) remains unknown for a single thruster let alone an array of engines.

What complicates the endeavor of characterizing the above processes is the fact that facility effects can have a profound impact on these measurements. Improper matching of engine test goals with a facility can render a series of experiments meaningless. For example, if the chamber is too small, its boundaries (walls) can affect measurements by altering the flowfield or by introducing contaminants due to tank wall erosion. Material sputtered from tank walls can interfere with measurements that use witness plates, samples, and QCMs to predict thruster and spacecraft material erosion. The electrical conductivity of tank walls in proximity to the engine (*i.e.,* within 1 m) has been shown to influence the electric field in the plume and the plume flow field.[26]

If the tank pressure is too high, the background gas can artificially modify the exhaust plume as well as alter the operation of the CDT itself. Thruster operation may be influenced by entrainment and/or ingestion of the background chamber molecules. This effect artificially increases the propellant mass flow rate of the engine, resulting in performance and operation changes consistent with the increased number of propellant particles. Furthermore, plume diagnostic experiments can be affected. A large partial pressure of background gas molecules can affect ion current density and energy distribution measurements by artificially increasing the local charge density through charge exchange collisions. For example, at large angles from the CDT axis, the ion energy distribution profile is dominated by low-energy charge exchange ions, the source of which is thought to be background gas, although neutral particles emanating from the cathode and thruster discharge chamber will contribute to this process as well.[19,24,27]

While there are no universally-accepted guidelines on facility pressure for CDT testing, Randolph *et al.*[26] suggest that in order to characterize a CDT in terms of performance, electromagnetic interference (EMI), far-field (≥1 m) plume properties, and life (and hence spacecraft contamination), the vacuum chamber pressure should be no more than $5x10^{-5}$, $5x10^{-5}$, $1.2x10^{-5}$, and $5x10^{-6}$ Torr,[∀] respectively. Since the pressures at low Earth orbit and at geosynchronous orbit are approximately $5x10^{-6}$ and $5x10^{-10}$ Torr, respectively, a perfect simulation of pressure is not always necessary. Randolph based his analysis on free-molecular flow, arguing that below a certain chamber pressure, thruster operating characteristics are not affected by the random flux of vacuum chamber particles. Conversely, if a thruster is tested above the specified pressure, the influence of background gas being ingested into the engine through free-molecular flow must be taken into account when analyzing test data. However, since Randolph based his pressure estimates on 1-kW-class thrusters where the internal pressure is expected to be approximately $5x10^{-4}$ Torr, it stands to reason that still lower pressures would be needed for high-power thrusters where internal pressures are lower. If we conserve the ratio of thruster discharge chamber pressure and tank pressure, we find that Randolph's estimates may be a factor of five too high for 50 kW engines. This is reflected in Table 1 which shows Randolph's original criteria for 1-kW-class thrusters, and the modified criteria for 50-kW-class CDTs.

As the table shows, chamber pressures between $1x10^{-6}$ and $1x10^{-5}$ Torr are needed to characterize high-power CDTs. However, Randolph's pressure criteria may not be strict enough even after correcting for thruster discharge chamber pressure. Figure 5 shows collimated and uncollimated Faraday probe data traces taken 1 m from the exit plane of the University of Michigan/AFRL 5-kW-class P5 CDT at the University of Michigan. The P5 was operating at 10 A - 500 V and the corrected chamber pressure was 6×10^{-6} Torr. While the chamber pressure satisfies Randolph's pressure criterion, the influence of the collimator is unmistakable. The collimator was used to remove low-energy ions created through charge-exchange (CEX) collisions in the plume. The figure clearly shows how facility effects can lead to an over-prediction of plume ion current density in the perimeter of the plume. This phenomenon was recently observed when integrated plume current density data from SPT-140 tests conducted at the University of Michigan and NASA GRC exceeded the thruster discharge current.[27] An explanation for this phenomenon was recently postulated by Haas.[28] Haas asserts that the Faraday probe electrode appears to low-energy CEX ions as a planar Langmuir probe. Since the collector electrode of a Faraday probe is typically biased 20 V below plasma potential to repel electrons, it can act as a point source potential sink to low-energy CEX ions in the perimeter of the plume where the plasma density is smallest and hence the sheath thickness is greatest. Therefore, the collimated current density data can be considered to be the profile that would exist in space where the population of CEX ions is expected to be small. Collimated current density data are also more in line with recent particle-in-cell code predictions.[29]

Figure 6 shows the background pressure of three large national electric propulsion vacuum facilities (*i.e.*, facilities not owned and operated by corporations) as a function of thruster power. These facilities include AFRL's Chamber 3 (xenon pumping speed of 150,000 l/s), the Large Vacuum Test Facility (LVTF) at the University of Michigan (245,000 l/s), and NASA Glenn Research Center's Tank 5 (2,000,000 l/s). The CHAFF-IV facility, with a predicted xenon pumping speed of 9,000,000 l/s,[30] was excluded from this chart because it is currently under development at USC. Also shown on the figure are Randolph's pressure criteria for performance, plume, and life measurements as a function of thruster power. As the figure clearly shows, none of the national test facilities shown can maintain an adequately-low background pressure to satisfy Randolph's pressure criteria for plume or life testing for a thruster power level of above 5 kW. Only NASA's Tank 5 can satisfies the performance criterion for a monolithic thruster with a power level up to 30 kW. In other words, strictly speaking, not even Tank 5 possesses adequate pumping speed to satisfy Randolph's performance pressure criterion for a 50 kW monolithic thruster. This fact was echoed recently both in a talk at the 35th Joint Propulsion Conference given by Robert Jankovsky of NASA GRC and at an AFOSR workshop on space-based electric propulsion testing in Norfolk, Virginia, in 1999.

∀ Corrected for xenon. The air-to-xenon hot cathode ionization gauge correction factor generally varies between 2.5 and 3.0, depending on gauge make.

Another interesting observation can be made from Figure 6; *only NASA's Tank 5 satisfies Randolph's performance criterion for thruster power levels above 5 kW.* Given the cost of adding pumping speed to a facility—between $1 and $4 per l/s—and the fact that most facilities are filled to capacity with cryosurfaces already, it is unlikely that a factor of ten or more improvement in pumping speed will take place by the time 50 kW CDTs (or CDT clusters) are being developed.

Table 1: Required chamber pressure as a function of CDT test activity from the analysis of Reference[26] for 1-kW- and 50-kW-class CDTs (300 V assumed).

CDT Test Activity	**Desired (1 kW) Pressure (Torr)**
Performance	5×10^{-5}
EMI	5×10^{-5}
Plume/Contamination	1×10^{-5}
Life/Erosion	5×10^{-6}
CDT Test Activity	**Desired (50 kW) Pressure (Torr)**
Performance	1×10^{-5}
EMI	1×10^{-5}
Plume/Contamination	2×10^{-6}
Life/Erosion	1×10^{-6}

In terms of chamber size, one could argue that since the characteristic length of a typical satellite is on the order of 10 m, the chamber should be of this size as well in order to make realistic plume measurements at a location from the exit plane that is representative of the distance actual flight hardware components are likely to be placed. Furthermore, the chamber should be as close to a sphere as possible with the thruster operating in the center so that a complete study of the plume can be made in all directions, and to maximize the path length that sputtered wall material must travel to the thruster. Both of these assertions are corroborated by Randolph's analysis which suggests that a cylindrical chamber with a length-to-diameter ratio of 1.2 (*i.e.*, close to spherical) and a characteristic length of several meters is optimum.[26] All of the national facilities referenced in Figure 6 satisfy these criteria. Moreover, other facility concerns associated with testing high-power thrusters (*e.g.*, vacuum seal thermal loading) can be addressed with straight-forward facility engineering such as water-cooled graphite beam dumps.

The message from this section is that national electric propulsion test facilities, while physically large enough to test 50 kW thrusters, posses pumping speeds that are at least an order of magnitude too low to ameliorate facility pressure effects for plume/contamination and life testing. Moreover, only NASA's Tank 5 satisfies Randolph's performance criterion for thruster power levels above 5 kW. As such, corrective measures must be developed to interpret test results in elevated chamber pressures even when testing a single node of a high-power CDT cluster.

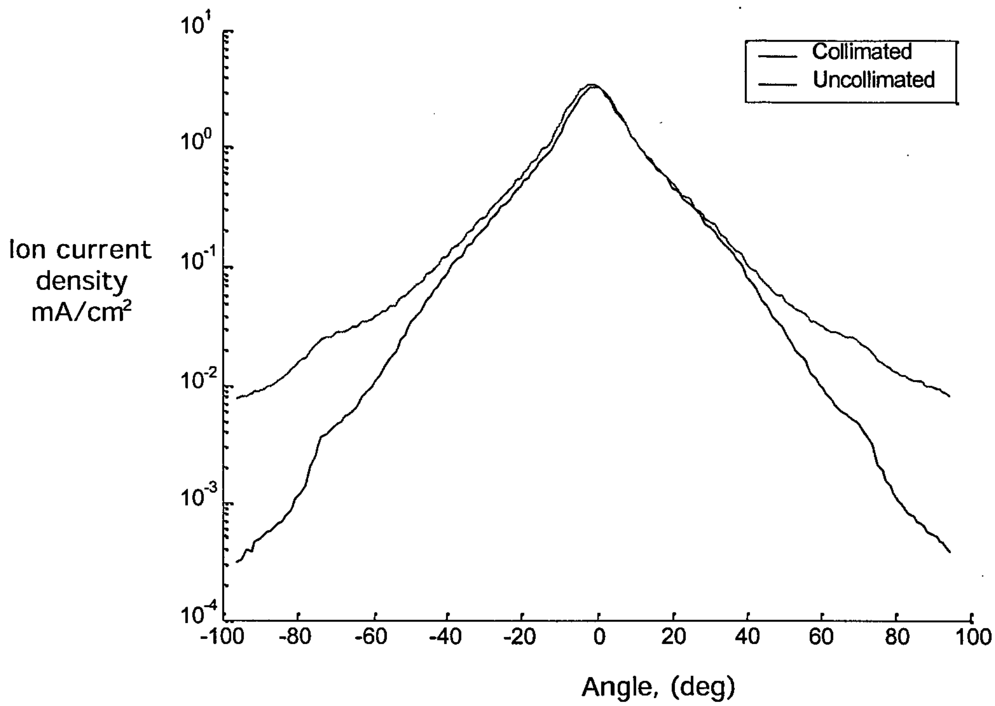

Figure 5: P5 ion current density vs. angle 1 m from thruster exit. (500 V, 10 A, $6.0x10^{-6}$ Torr (Xe))

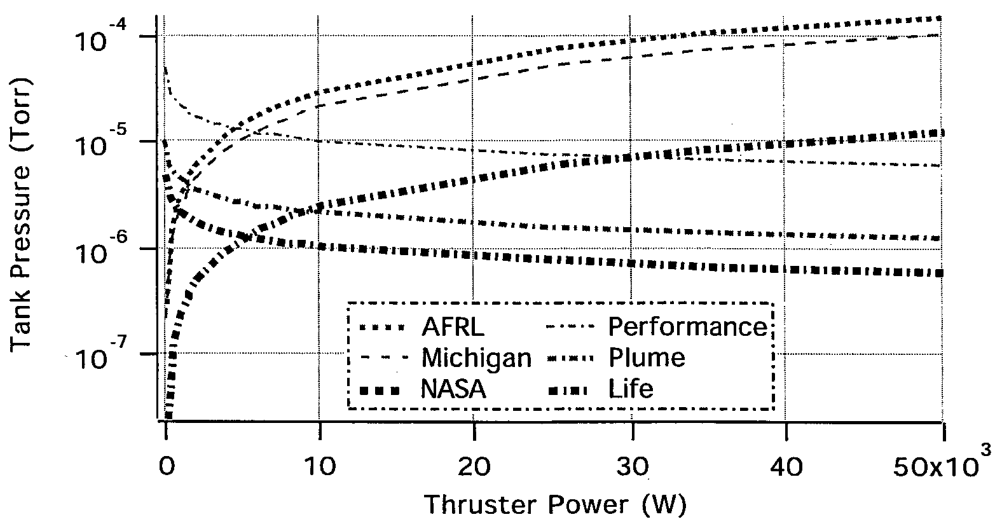

Figure 6: Vacuum Chamber Pressure vs. Thruster Power for AFRL Chamber 3 (150 kl/s), the University of Michigan Large Vacuum Test Facility (240 kl/s), NASA Glenn Research Center Tank 5 (2,000 kl/s). All pumping speeds are for xenon.

Proposed Research Effort

Research Proposal Summary

CDTs have great potential in satisfying many of the spacecraft propulsion needs of the USAF for the next several decades. Its combination of high specific impulse, high thrust efficiency, and high thrust density makes it very attractive for a number of earth-orbit space missions. The USAF has recently identified the high-power (*e.g.*, 100-150 kW) CDT cluster as the primary propulsion system for future missions. While the evolutionary path for scaling current 5-kW-class CDTs to 50 kW is uncertain because of thermal loading issues, plume neutralization matters, and overall scaling concerns, it is clear that testing 50-kW-class CDTs or CDT clusters in current or expected test facilities is an issue due to facility pumping speed limitations.

Given the fact that an order-of-magnitude increase in pumping speed would be necessary to satisfy pressure requirements, it is likely that high-power CDTs and CDT clusters will have to be developed using test-facilities with less than ideal pumping speeds. The solution to this dilemma is to develop tools to correct for facility effects when making performance, plume, and lifetime measurements. While the ultimate tool may be numerical in nature, a great deal of basic measurements need to be made to help develop this design tool and to validate it. Moreover, much can be gained by developing operating procedures, simple correction factors, or probes (*e.g.*, collimated Faraday probes) to take into account facility effects. While facility requirements needed to test a single node of a CDT cluster are far less demanding than those for a monolithic thruster, facility pressure correction factors will still be needed since only NASA's Tank 5 has the pumping speed necessary to perform plume and life tests for an 8-10 kW CDT according to Randolph's criteria (cf. Figure 6).[26]

To this end, we recently[Π] submitted a proposal to AFOSR to address this issue in a three-year program. If funded, our program will:

1) Evaluate Randolph's pressure criteria (and all others used throughout the field) and establish new guidelines for high-power CDT and CDT cluster testing. For example, Randolph used life test criteria established for ion thrusters on the basis of residual air in the vacuum chamber since oxygen and nitrogen can coat molybdenum grids, making them more resistant to sputtering. Since the failure mechanism is different for Hall thrusters (which also employ different materials such as boron nitride), new guidelines are needed;
2) Characterize how thruster/cluster performance is affected by facility pressure;
3) Determine how chamber pressure influences beam divergence, ion energy distribution, plume ionization state, and the transport of contaminants (*e.g.*, thruster erosion products) for both a cluster and a single engine;
4) Investigate what role chamber pressure has on thruster/cluster erosion and spacecraft/neighboring thruster contamination; and
5) Collaborate heavily with the AFRL, Professor Iain Boyd[#], an expert in plume modeling, BUSEK, and TsNIIMASH, which is conducting clustering work as well.

Our goals are through basic research to provide insight on:

1) How chamber pressure influences engine operating characteristics,
2) Identifying critical issues for CDT clusters;
3) How one can test a cluster element (thruster) and extrapolate the results for the cluster; and
4) Providing guidelines/diagnostics/procedures for testing high-power monolithic and clustered CDTs at elevated tank pressures.

We believe such insight is necessary before design/testing tools can be developed.

[Π] Proposal was submitted to AFOSR in May 2001 (AFOSR control number 01-NA-288)
[#] By dedicating a graduate fellowship student to support this work through modeling.

Thrusters

A number of thrusters and thruster clusters will be used for this research. These propulsion systems include (Figure 7):

1) The 5-kW-class P5 laboratory-model thruster developed under AFOSR funding by the University of Michigan and AFRL;
2) The 200-W-class BUSEK BHT-200 CDT, the primary propulsion system for TechSat21;
3) The 2x2 200 W cluster composed of BUSEK BHT-200 CDTs;
4) (Possibly) The 4x 600 W cluster composed of BUSEK BHT-HDC-600;[Δ] and
5) (Optional) BUSEK racetrack thrusters are also available at no cost.

Though designed to operate at 15 A – 300 V, the P5 will be operated at low current (~5 A) to simulate the low internal pressure of a 50 kW CDT, and high current (25 – 30 A) to investigate high-power conditions that tax both the vacuum facility and probe-diagnostics (thermally). The P5 has demonstrated its capability of operating at power levels above 9 kW at 15 A. Thus the P5 will be operated at the following three conditions (at 300 or 350 V):

1) 5 A - to simulate the lower internal pressure of a 50 kW CDT;[∞]
2) 15 A - to compare nominal conditions at high and low pressure; and
3) 25 A - high flow rate and power condition to tax the facility and diagnostics.

To provide the last condition, a second Sorenson laboratory power supply (16 A—600 V) will be operated in parallel with our existing supply. This combination will allow for discharge currents above 30 A at 600 V. The second supply (a Sorenson PRO-600-16T5) was recently purchased under existing AFOSR funding. This supply will also facilitate the operation of a 2x1 P5 cluster (see below). All other support equipment necessary to operate at these three conditions (*e.g.*, propellant flow systems) are already in place.

Additional CDTs will be employed to expand the test matrix. BUSEK and the AFRL will provide a single 200-400 W CDT (BUSEK BHT-200) and a 2x2 cluster of these engines, respectively at no cost. Since vacuum tank pressures in the mid-to-high 10^{-7} Torr range can be maintained for the BHT-200, this engine will serve as the baseline thruster where facility effects are assumed to be negligible. Extensive plume and performance measurements with the 2x2 cluster of BHT-200s will be performed as well. Hence, we will use the BHT-200 plume and performance tests as the baseline for both the 'zero' pressure test condition for a monolithic thruster and for extrapolating single-engine test data to a cluster.

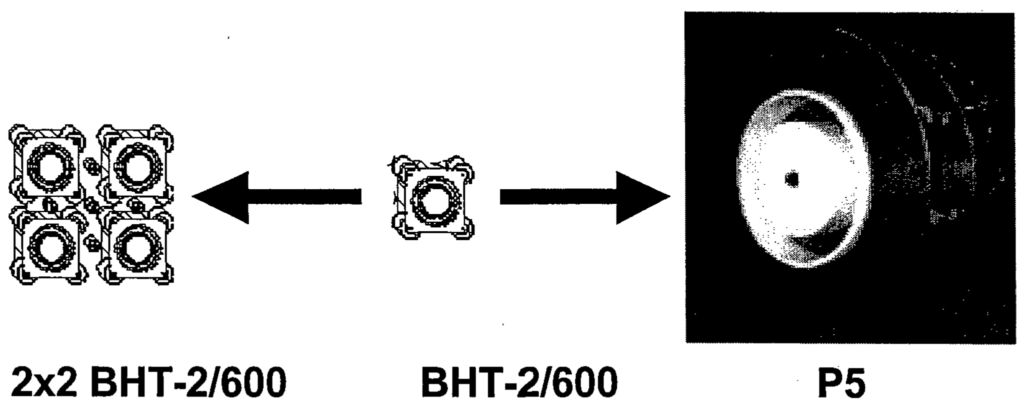

Figure 7: Conceptual diagram of thruster test matrix (200—9000 W).

Δ The 4x 600 W cluster would not be available before 2004. It would be on loan from the AFRL
∞ Since the P5 is routinely operated at 5 A – 300 V, there is no issues associated with operating the engine at this low-pressure condition.

Since many of the issues of concern regarding clustering thrusters may not surface until extensive cluster testing commences, a joint AFRL-University of Michigan cluster program is taking place this summer at the AFRL. University of Michigan graduate student Brian Beal will work at the AFRL this summer with AFRL personnel to conduct tests with the 2x2 BHT-200 cluster. The work this summer is expected to uncover critical issues and thus is an excellent way of guiding our research. Discussions are in progress between PEPL and the AFRL about building a second P5 Hall thruster and operating a 2x1 P5 cluster, with a maximum power approaching 20 kW, in the LVTF next year. The funds requested in this proposal for LVTF modifications will facilitate this experiment as well.

Test Plan

The research will take place at the University of Michigan Plasmadynamics and Electric Propulsion Laboratory (PEPL), the AFRL, and BUSEK. All testing at the PEPL will be performed in the 6-m-diameter by 9-m-long Large Vacuum Test Facility (LVTF) (see *Existing Experimental Facilities* section below). Through the use of 7 internal (nude) cryopumps, the LVTF is capable of achieving a xenon pumping speed of 245,000 l/s. The LVTF's modular cryopumping system enables any combination of the seven cryopumps to be operated, resulting in a wide range of background pressures for a given thruster power level (see Figure 8). In addition, xenon can be bled into the chamber to elevate the pressure. The combination of reducing the number of pumps and bleeding in xenon will enable us to investigate facility pressure effects thoroughly for the engines and engine clusters dedicated to this effort. We will now provide details on how facility effects on performance, plume characteristics, and erosion will be investigated.

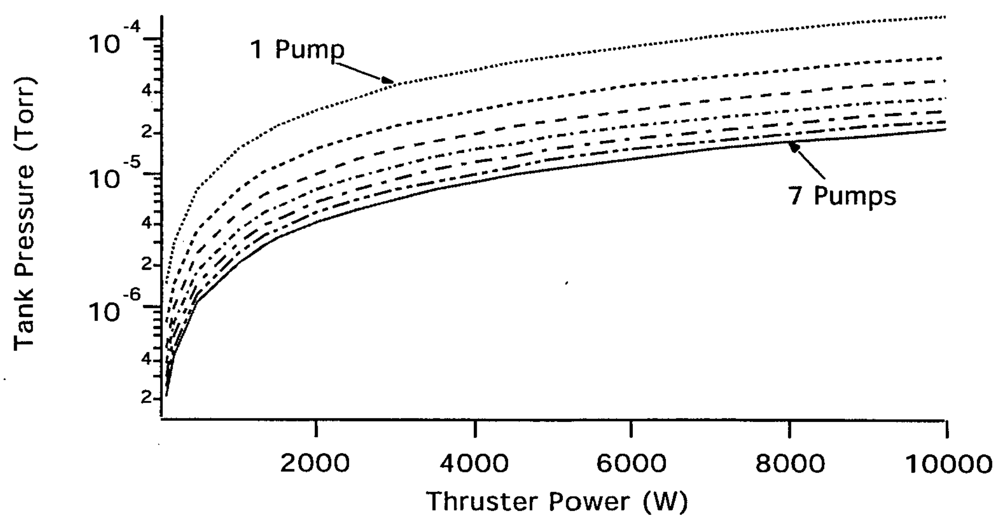

Figure 8: LVTF Pressure vs. Thruster Power (@ 300 V) with 1 - 7 pumps on.

Facility Effects on Engine Performance

To investigate the influence of chamber pressure on engine performance, the P5, the BHT-200, and the 2x2 BHT-200 cluster will be tested on a thrust stand at various tank pressures. Thrust will be measured on a NASA GRC inverted pendulum thrust stand, which is the standard used for steady-state electric propulsion engines. This thrust stand was used to measure the performance of 1 kW arcjets, the P5 (Figure 7), and commercial 5 kW CDTs such as the Generally Dynamics BPS-4000 and the Pratt & Whitney T-140. Specific impulse will be determined by combining thrust measurements with propellant flow rate measurements obtained with calibrated, commercial thermal mass flow controllers.

To determine how the background gas particles affect engine operation and performance, the following set of very-near-field (VNF) — exit plane to 10 cm — and for the P5 only, internal measurements will be made at low and elevated tank pressures:

5) Emissive probe to map plasma potential;
6) Langmuir probe for electron temperature, number density, electron energy distribution function, and floating potential;
7) Hall or Bdot probes to measure magnetic fields;
8) 35-GHz microwave interferometer for electron number density and plasma fluctuations to look for 'cross-talk' among in the clustered thrusters that may cause the growth of instabilities;
9) Laser Induced Fluorescence (LIF) to measure ion and neutral velocity, temperature, and relative density; and
10) ExB probe and/or Miniature Ion Energy Analyzer (see below) for ion energy distribution.

To facilitate making probe measurements in the VNF and inside the P5 with minimum perturbation to the thruster, our High-speed Axial Reciprocating Probe (HARP) positioning system will be used. HARP is an electromagnetic probe table which can place probes in and out of the P5 on timescales of 100 msec or less.[29] This short probe residence time prevents probe ablation, and minimizes the global perturbation of the thruster from the probe. Use of the HARP with Langmuir and emissive probes caused only a slight perturbation in the P5 discharge current (less than 5% and 15%, respectively of nominal) during all measurements. Internal measurements are baselined only for the P5 because of the small channel widths of the BHT-200. We feel it is critical to understand what influence vacuum tank pressure has on the internal flow field of the engine. We will also investigate the possibility of using the HARP system for the much smaller BHT-200 as well.

Facility Effects on Engine Plume Characteristics

To aid in the development of numerical, procedural, or corrective tools for plume testing at elevated pressures, we propose to subject the P5, the BHT-200, and the 2x2 BHT-200 cluster to a battery of far-field (0.5 – 1.5 m) plume diagnostics over a wide range of yaw [and roll angles for the cluster] ($\pm 100^{\circ}$). The diagnostic tools that will be employed include:

1) Nude and collimated Faraday probes to measure ion current density/plume divergence;
2) Molecular Beam Mass Spectrometer (MBMS), a time-of-flight mass spectrometer with a 45-degree electrostatic energy analyzer, for making ion energy and mass spectral measurements;
3) Miniature Ion Energy Analyzer (MIEA) — miniature version of the (MBMS) 45-degree electrostatic energy analyze — to make ion energy measurements;
4) ExB probe for measuring ion velocity, energy distribution function, and ionization state of the plume;
5) LIF to measure ion velocity (energy), temperature, and relative density;
6) Emissive probe to measure plasma potential;
7) Witness plates for contamination studies (particularly with regard for cluster and cluster element testing); and
8) A commercial Langmuir probe system (by Hiden) will be used to measure electron temperature, number density, electron energy distribution function, and floating potential.

The measurements would be made at the same thruster/cluster operating and vacuum chamber conditions used for the performance study and VNF plume measurements described above. By determining how these plume properties change with background pressure, we not only provide invaluable data to facility effect modelers such as Professor Iain Boyd or AFRL's Dr. Michael Fife, but we will be able to develop procedures to correct for facility effects and for extrapolating the characteristics of one thruster to that of a cluster.

Cluster Issues to Address

Given the fact that very few experiments have taken place with CDT clusters, many of the challenges that face high-power modular CDT systems have yet to be identified. While joint AFRL-Michigan cluster experiments this summer with the 2x2 BHT-200 cluster are expected to identify many of these challenges, a few questions can be readily identified:

9) How does the thrust of a single engine scale for a cluster?
10) How does the plume of an engine affect the performance of a neighboring engine; *e.g.,* through ingestion of xenon neutrals, charge-exchange ions, or erosion products?
11) How does the plume of an engine affect the life of a neighboring engine; *e.g.,* through sputtering from high-angle ions?
12) How does the plume profile of a cluster compare to that from a single engine?
13) Is there any cross-talk among clustered engines that can cause instabilities to grow?
14) Does a cluster affect EMI and communication signal transmission in a profoundly different manner than a single engine?
15) How many neutralizers are needed for a cluster and is there an optimum position for them?
16) Are pressure criteria for a single engine applicable to a cluster?
17) Are there subtle procedural differences in testing a cluster vs. a monolithic thruster?

While many others will arise, we believe our research program will provide the answers to many of the above questions and to those not yet asked.

Existing Experimental Facilities

The Plasmadynamics and Electric Propulsion Laboratory (PEPL) performs research on spacecraft plasma propulsion and space plasma physics. Though it is housed within the Aerospace Engineering Department, faculty from Nuclear Engineering, Electrical Engineering, and Space Physics participate in PEPL research.

PEPL operates two vacuum facilities for plasma physics research; the LVTF and the CTF. The Large Vacuum Test Facility (Figure 9) is 9 meters long and 6 meters in diameter and is the largest vacuum facility of its kind at any university in the nation. This facility, which is used to test Hall thrusters and ion engines, is evacuated by seven LN_2-cooled CVI TM1200 reentrant (nude) cryopumps that give the facility an overall pumping speed of 500,000 l/s on nitrogen, 245,000 l/s on xenon, and a base pressure of less than 2×10^{-7} Torr. The Cathode Test Facility (not shown) is a 3-m-long by 60-cm-diameter chamber that is pumped by a CVI TM500 cryopump with a nitrogen pumping speed of 3,500 l/s, a xenon pumping speed of 1,750 l/s, and a base pressure of 2×10^{-8} Torr. The CTF is used to test hollow cathodes and Field Emitter Array cathodes and will be the initial testbed for our laser diagnostic technique to measure CDT discharge chamber (boron nitride) erosion. The proposed cluster research will be performed in the LVTF. PEPL operates a wide range of diagnostics including mass and optical spectrometers, energy analyzers, electrostatic probes actuated with high-speed tables, microwave diagnostics systems, and a huge suite of diagnostics lasers.

One of the benefits of developing a cluster test capability at PEPL is our vacuum facility. Currently, Chamber 6 at the AFRL is dedicated to cluster testing. While a good facility, Chamber 6 is approximately a factor of ten smaller both in volume and pumping speed than the LVTF. Moreover, the AFRL Chamber 3—a 150 kl/s facility—will be dedicated for at least the coming year to the SPT-140 life test. Thus, equipping the LVTF to test clusters is necessary if the USAF is going to evaluate cluster operation in a high-capacity vacuum facility in the near future.

As was mentioned earlier, discussions are in progress between PEPL and the AFRL about building a second P5 Hall thruster and operating a 2x1 P5 cluster, with a maximum power approaching 20 kW, in the LVTF next year. The funds requested in this proposal for LVTF modifications will allow for this experiment to take place as well.

DURIP Request

DURIP funds were used to purchase the following items:

1) A BUSEK 2x2 600 W Hall thruster/cathode cluster centered around the BHT-600;
2) Associated power supplies, propellant feed systems, and vacuum chamber penetrations to run the 2x2 600 W BUSEK cluster;
3) A high-performance, high-capacity rotary table for roll or yaw articulation of the cluster to investigate plume asymmetry. Either the cluster or probe assembly would be rotated with this high-capacity unit. We already posses the needed hardware and software drivers for this system. This system would be robust enough to investigate plume asymmetry in even the heaviest cluster proposed—the 2x1P5 cluster (~30 kg); and
4) Funds to convert our NASA-style inverted-pendulum thrust stand to a newer Null-type derivative, the approach now used at NASA and AFRL. Converting our system to a Null-type derivative will improve our ability to characterize cluster performance and will facilitate the comparison of performance data collected at PEPL and AFRL. The new stand would also allow performance measurements to be made with the 2x1 P5 cluster, which will produce a thrust approaching 1 N.

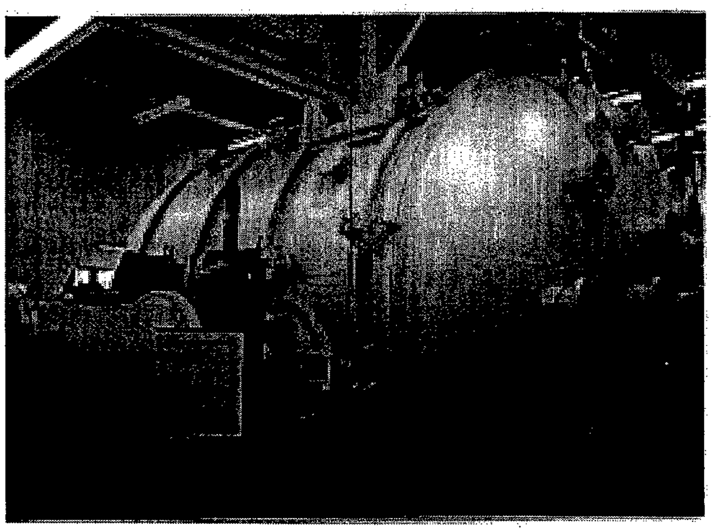

Figure 9: The main vacuum chamber of PEPL—the Large Vacuum Test Facility (LVTF). This 9-m-long by 6-m-diameter chamber is supported by seven large cryopumps, giving it a pumping speed in excess of 500,000 l/s on air and 240,000 l/s on xenon.

The BUSEK cluster requested (Fig. 10) is identical to the one delivered to the AFRL this past summer. While our research plans currently call for this cluster to tested at both AFRL and PEPL, our research would be greatly enhance by having a cluster at each facility. A second cluster would benefit the Air Force research effort by:

1) Allowing for experiments to be conducted in parallel at both AFRL and PEPL;
2) Reducing the likelihood of cluster damage during transportation;
3) Freeing us to make all necessary modifications to the cluster to advance the research; *e.g.*, putting holes in the discharge chamber of a thruster for internal access; and
4) Offering the potential to operate two clusters simultaneously; *i.e.*, eight Hall thrusters at once.

Moreover, the enhanced capability of the LVTF to operate the requested BUSEK cluster would be used for a variety of higher-power clusters; *e.g.*, the BUSEK 2x2 600 W and the 2x1 P5.

Figure 10: Picture of the BUSEK 2x2 600 W Hall Thruster Cluster purchased with DURIP funds.

Expenditure Summary

A total of $160,400 is requested from DURIP out of a total estimated cost of $200,400 for the entire acquisition. The University of Michigan provided $40,000 of cost-sharing; 25% of the requested amount and 20% of the total. A summary of the cost proposal is shown as Table 2. As per proposal preparation instructions, the description, model number, vendor, contact person and telephone number, per unit cost, and quantity requested for each item of equipment is listed. All prices reflect figures provided via recent quotations. NO INDIRECT COSTS WAS CHARGED TO THIS GRANT.

<u>Review of Budget Items for the Hall Thruster Cluster Test Facility</u>

Major items that are requested of DURIP plus cost-sharing funds include:

1) Four (one per thruster) Sorenson DCS 600-1.7 power supplies for cathode ignition and to power the cathode keeper of each cluster thruster;
2) Eight (2 per thruster) Sorenson DLM 40-15 power supplies for the four cluster cathode heaters and four thruster magnets;
3) Four (one per thruster) Sorenson DHP 600 V — 5 A discharge power supplies;
4) Four (one per thruster) MKS 10 sccm cathode flow controllers for each thruster;
5) Four (one per thruster) MKS 100 sccm anode flow (main flow) controllers for each thruster;
6) Two MKS Type 247 4-channel units to monitor and control mass flow rates;
7) Miscellaneous cables and rack-mounted thruster power distribution boxes;
8) A new vacuum chamber flange with penetrations (feed-thrus) for cluster power and propellant;
9) A BUSEK 2x2 600 W Hall thruster/cathode cluster (cf. Fig. 10);
10) An Aerotech high-precision, high-load rotary table*; and

* This unit will be controlled by our existing Aerotech table control system.

11) Fund to convert our moving, inverted-pendulum thrust stand to a Null-type unit (now the industry standard).

Table 2: DURIP cost summary.

Item	Unit Price	Quantity	Total Item Price
DCS 600-1.7 Ignitor/Keeper Supply	$ 1,450	4	$ 5,800
DLM 40-15 Cathode Heater Supply and Magnet Supply	$ 1,400	8	$ 11,200
DHP 600 V-5 A (3 kW) Discharge Supply	$ 3,300	4	$ 13,200
10 sccm flow controllers (for cathodes)	$ 1,400	4	$ 5,600
100 sccm flow controllers (for discharge)	$ 1,400	4	$ 5,600
Type 247 4-channel readout/controller	$ 1,450	2	$ 2,900
Controllers-to-Readout Cables	$ 200	8	$ 1,600
Rack-mounted power distribution boxes	$ 1,000	4	$ 4,000
Flange outfitted with power and propellant feed-thrus	$ 1,000	1	$ 1,000
2x2 600 W Thruster/Cathode Cluster	$ 140,800	1	$ 140,800
ART320-UA-G108/VAC6-BMS-HC rotary stage	$ 7,500	1	$ 7,500
Thrust stand modifications to go to a null system	$ 1,200	1	$ 1,200
		List Sum:	**$200,400**

Figure 11: Picture of the new null-type thrust stand developed with DURIP funds.

Summary and Conclusions

DURIP funds were employed to develop a Hall thruster cluster test facility centered around the University of Michigan Large Vacuum Test Facility and a 2x2 cluster of 600 W BHT-600 Hall thrusters. This capability will help us carry out our three-year goal addressing the issue of high-power cluster operation by: (1) Characterizing how monolithic and clustered thruster performance is affected by facility effects; (2) Determining how chamber effects influence beam divergence, ion energy distribution, plume ionization state, and the transport of contaminants (*e.g.*, thruster erosion products) for both monolithic and clustered thrusters; and (3) Investigating what role chamber pressure has on thruster erosion and engine life for monolithic and clustered thrusters. We will use several engines/engine clusters for this investigation including the 1-9 kW P5 laboratory-model thruster—developed under AFOSR funding—the 2x2 BHT-200, the 2x2 BHT-600 cluster requested in this proposal, and a single 600 W BHT-200 CDT from this cluster.

We will continue to collaborate heavily with the AFRL, Professor Iain Boyd (an expert in plume modeling), and BUSEK on this project. Once our cluster is operational, experiments will be conducted in parallel both at the Plasmadynamics and Electric Propulsion Laboratory (PEPL) and at AFRL, which already posses this cluster. Our goal is to provide insight on how chamber effects influence these engine/cluster characteristics. We believe such insight is necessary before a design/testing tool can be developed.

References

[1] Gulczinksi, F. S., and Spores, R. A., "Analysis of Hall-Effect Thrusters and Ion Engines for Orbit Transfer Missions, " AIAA-96-2973, 32nd Joint Propulsion Conference, July 1996.

[2] Sutton, G. P., Rocket Propulsion Elements, Sixth Edition, John Wiley & Sons, Inc., New York, 1992.

[3] Deininger, W. D., "Advanced Propulsion System Options for Geostationary Satellites," AIAA-94-3001, 30th Joint Propulsion Conference, Indianapolis, IN, June 27-29,1994.

[4] Jahn, R. G., Physics of Electric Propulsion, McGraw Hill Book Company, NY, 1968.

[5] Pivirotto, T., King, D., Deninger, W., and Brophy, J., "The Design and Operating Characteristics of a 30 kW Thermal Arcjet Engine for Space Propulsion," AIAA-86-1508, 22nd Joint Propulsion Conference, Huntsville, Alabama, June 16-18,1986.

[6] Curran F. M., Bullock, S. R., Haag T. W., Sarmiento, C. J., and Sankovic J.M., "Medium Power Hydrogen Arcjet Performance," AIAA-91-2343, 27th Joint Propulsion Conference, Sacramento, California, June 24-27, 1991.

[7] Carney, L. M., and Sankovic, J. M., "The Effects of Arcjet Thruster Operating Conditions and Constrictor Geometry on the Plasma Plume," AIAA-89-2723, (NASA TM-102285), presented at the 25th Joint Propulsion Conference, Monterey, California, July 10-12, 1989.

[8] Gallimore, A. D., Myers, R. M., Kelly, A. J., and Jahn, R. G., "Anode Power Deposition in an Applied-Field Segmented Anode MPD Thruster," Journal of Propulsion and Power (AIAA) Vol. 10, No. 2 March-April, 1994, pp. 262-268.

[9] Sovey, J. S., and Mantenieks, M. M., "Performance and Lifetime Assessment of Magnetoplasmadynamic Arc Thruster Technology," J. Propulsion, Vol. 7, No. 1 Jan--Feb, 1991, pp. 71-83.

[10] Patterson, M. J., "Performance Characteristics of Ring-Cusp Thrusters with Xenon Propellant," AIAA-86-90, 22nd Joint Propulsion Conference, Huntsville, Alabama, July 16-18, 1986.

[11] Aston, G., Brophy, J., Garner, C., and Pless, L., "A Xenon Ion Propulsion Module for Enhanced Spacecraft Capability," AIAA-86-1393 22nd Joint Propulsion Conference, Huntsville, Alabama, June 16-18,1986.

[12] Kaufman, H. R., "Technology of Closed-Drift Thrusters," AIAA-83-1398, 19th Joint Propulsion Conference, Seattle, Washington, June 27-29, 1983.

[13] Brown,C. O., and Pinsley, E. A., "Further Experimental Investigations of a Cesium Hall-Current Accelerator," AIAA Journal, Vol. 3, No. 5, May, 1965, pp. 853-859.

[14] Chubb, D. L. and Seikel, G. R., "Basic Studies of a Low Density Hall Current Ion Accelerator," (NASA TN D-3250), Feb.,1966.

[15] Kaufman, H. R., Robinson, R. S., Day, M. S., and Haag, T. W., "End-Hall Thrusters," AIAA-90-2595, 21st International Electric Propulsion Conference, Orlando, FL, July 18-20, 1990.

[16] Burgrova, A. I., Yermakov, Y. A., Morozov, A. I., and Yakunin, S. A., "A New Stage of Stationary Plasma Engine (SPE) Development," presented at the *Anniversary Specialist Conference on Nuclear Power Engineering in Space*, Institute of Physics and Power Engineering, Obninsk, May~15-19, 1990.

[17] Morozov, A. I., Shubin, A. P., and Elizarov, L. I., "Modern State and Future of Electric Propulsion Thrusters," presented at the *Anniversary Specialist Conference on Nuclear Power Engineering in Space*, Institute of Physics and Power Engineering, Obninsk, May 15-19, 1990.

[18] Haas, J. M., Gulczinski, F. S., Gallimore, A. D., Spanjers, G.G., and Spores, R. A., "Performance Characteristics of a 5 kW Laboratory Hall Thruster," AIAA-98-3503, 34th Joint Propulsion Cleveland, OH, July 12-15, 1998.

[19] Sankovic, J., Caveny, L., and Lynn, P. "The BMDO Russian Hall Electric Thruster Technology (RHETT) Program," AIAA-97-2917, 33rd Joint Propulsion Conference, Seattle, WA July 6-9, 1997.

[20] Martinez-Sanchez, M., "Some Thoughts on Thruster Scaling," presented at the AFOSR Workshop on Electric Propulsion for Small Satellites, Chicago, IL, May 19, 1995.

[21] Pote, B., Hruby, V., and Monheiser, J., "Performance of an 8 kW Hall Thruster," IEPC-99-080, 26th International Electric Propulsion Conference, Kitakyushu, Japan, Oct. 1999.
[22] Marrese, C., Polk, J. E., King, L. B., Garner, C., Gallimore, A. D., Semenkin, S., Tverdoklebov, S., and Garkusha, V., "Analysis of Anode Layer Thruster Guard Ring Erosion,": Proceedings of the 24th International Electric Propulsion Conference, Moscow, Russia, Sept. 1995.
[23] Gulczinski III, F. S., Examination of the Structure and Evolution of Ion Energy Properties of a 5 kW Class Laboratory Hall Effect Thruster at Various Operational Conditions, Ph.D. thesis, Dept. of Aerospace Engineering, The University of Michigan, Aug., 1999.
[24] King, L. B., and Gallimore, A. D., "Ion Energy Diagnostics in the Plume of an SPT-100 from Thrust Axis to Backflow Region," AIAA-98-3641, 34th Joint Propulsion Cleveland, OH, July 12-15, 1998.
[25] Randolph, *et al.*, "Facility effects on SPT thruster testing," IEPC-93-093, 23rd International Electric Propulsion Conference, Seattle, Washington, Sept. 13-16, 1993.
[26] Kusamoto, D., Mikami, K., Komurasaki, K., and Gallimore A. D., "Exhaust Beam Profiles of Hall Thrusters," Transactions of Japanese Society for Aeronautical and Space Sciences, Vol. 40, No.130, 1998, 238-247.
[27] Fife, J. M., Hargus, W. A., Jaworski, D., Jankovsky, R., Mason, L., Sarmiento, C., Snyder, J. S., Malone, S. P., Haas, J., M., and Gallimore, A. D., "Spacecraft Interaction Test Results of the High Performance Hall System SPT-140," AIAA 2000-3521, 36th AIAA/ASME/SAE/ASEE Joint Propulsion, Huntsville, Alabama, 16-19 July 2000.
[28] Haas, J. M., Low-Perturbation Interrogation of the Internal and Near-field Plasma Structure of a Hall Thruster using a High-Speed Probe Positioning System, Ph.D. thesis, Dept. of Aerospace Engineering, The University of Michigan, Feb., 2001.
[29] Personal Communication, Iain Boyd, The University of Michigan, Fall 2000.
[30] Lufty, F. M., Green, A. A., Muntz, E. P., Ketsdever, A. D., "Investigation of the Operational Envelope of the CHAFF-IV Plume and Contamination Thermospheric Flow Simulator," AIAA 99-2719, 35th Joint Propulsion Conference, June, 1999.